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Condition Monitoring of the Power Output of Wind Turbine Generators Using Wavelets

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Abstract—With an increasing number of wind turbines being erected offshore, there is a need for cost-effective, predictive, and proactive maintenance. A large fraction of wind turbine downtime is due to bearing failures, particularly in the generator and gearbox. One way of assessing impending problems is to install vibration sensors in key positions on these subassemblies. Such equipment can be costly and requires sophisticated software for analysis of the data. An alternative approach, which does not require extra sensors, is investigated in this paper. This involves monitoring the power output of a variable-speed wind turbine generator and processing the data using a wavelet in order to extract the strength of particular frequency components, characteristic of faults. This has been done for doubly fed induction generators (DFIGs), commonly used in modern variable-speed wind turbines. The technique is first validated on a test rig under controlled fault conditions and then is applied to two operational wind turbine DFIGs where generator shaft misalignment was detected. For one of these turbines, the technique detected a problem 3 months before a bearing failure was recorded.

Index Terms—Condition monitoring, electrical generator, signal processing, wind energy, wind turbines.

I. INTRODUCTION

INCREASING land constraints across Europe have led to the development of wind farms offshore with new challenges, particularly with regard to operations and maintenance. Access to turbines for maintenance and repair may be significantly restricted during periods of high wind speed and significant wave height, particularly during the winter. It has been suggested that operations and maintenance costs for offshore wind farms could account for up to 30% of the energy costs [1]. There is a need, therefore, for early warning when problems may be about to occur for a particular wind turbine. Condition monitoring is

seen as a way to reduce operations and maintenance costs for wind turbines [2].

The number of wind turbine failures due to the gearbox and generator subassemblies in modern wind turbines has been shown to be significant [3] and the downtime due to such failures is more significant due to procurement times and the need to winch these heavy subassemblies in and out of the nacelle.

It has been suggested that spectral analysis of the power output signal can be used to monitor not only rotor blade unbalance [4] but also gearbox and bearing faults [5]. However, in general to date, more conventional vibration sensor approaches have been favored [6]–[8].

Bearing problems account for between 21% and 95%, respectively, of all failures [9] in electrical machines, and for induction machines of the size and type used in wind turbines this figure is probably >45%. Therefore, early detection of such problems would significantly reduce wind turbine downtime if maintenance could then be planned in advance. Vibration monitoring has been applied to conventional power generation with generators running at a fixed frequency and current monitoring has been deployed, primarily motor current signature analysis (MCSA), for inferring problems due to broken rotor bars and air gap eccentricity, e.g., [10]–[12]. Instantaneous power has also been used to monitor such faults [13], including in the case of a wind turbine generator [14]. Indeed, the monitoring of power, as opposed to current, may yield more information with regard to induction machine faults [15] because of its ability to deal with all three phases under both balanced or unbalanced conditions. More recently, work has extended to monitoring instantaneous power to detect bearing damage [16].

The use of wavelets in the analysis of electrical machine current waveforms has been established for fault diagnosis of rotor eccentricity in a brushless dc machine [17] and in the detection of broken rotor bars in an induction machine [18]. These examples have employed steady-state monitoring. The monitoring by wavelets of transient current signals during machine start-up can also yield useful information with respect to broken rotor bars [19]–[23]. Although there has been much work looking at the application of wavelets and Fourier transforms to the detection of broken rotor bars, this type of failure represents a negligible fraction of generator faults in wind turbines. More recently, the use of wavelets for detecting shaft misalignment and bearing problems using the power signal has been demonstrated for the condition monitoring of variable speed wind turbines [24]. The use of wavelets has an advantage over Fourier analysis when analyzing nonstationary signals, such as are seen in variable speed electrical machines.

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In this paper, we present the analysis of the power output of a DFIG by the use of wavelets to detect rotor eccentricity. The theory behind the wavelet analysis is presented and the principle of analyzing particular frequency components characteristic of mechanical and electrical faults is established. The method is then applied to a laboratory test rig under known fault conditions, first in fixed and then in variable-speed operation. Finally, the method is applied to two operational, variable-speed, pitch-regulated wind turbines with DFIGs (1.5 and 2.5 MW, respectively), where rotor eccentricity was detected and, in the case of one of these turbines, well in advance of an eventual bearing failure.

II. MATHEMATICAL ANALYSIS OF INDUCTION MACHINE POWER OUTPUT

A. Characteristic Signatures in Power Output

For an induction machine where static and dynamic eccentricity may be present, fault characteristics at a frequency of $f_1 \pm mf_r$ in the stator current [13] will appear where f_1 is the supply frequency, f_r is the machine rotational frequency and m is a positive integer. This component manifests itself in the instantaneous single-phase power as in (1)

$$p(t) = \frac{\sqrt{3}}{2} \times \left\{ U_{m1} I_{m1} [\cos(2\omega_1 t - \varphi) + \cos \varphi] + \sum_{m=1}^{\infty} \left\{ U_{m1} I_{ecpm} \begin{bmatrix} \cos((2\omega_1 - m\omega_r)t - \varphi_{ecpm}) \\ + \cos(m\omega_r t + \varphi_{ecpm}) \end{bmatrix} + U_{m1} I_{ecnm} \begin{bmatrix} \cos((2\omega_1 + m\omega_r)t - \varphi_{ecnm}) \\ + \cos(m\omega_r t - \varphi_{ecnm}) \end{bmatrix} \right\} \right\} \quad (1)$$

where

U_{m1}	maximum value of the supply line-to-line voltage;
I_{m1}	maximum value of the fundamental supply current;
I_{ecpm}	maximum value of the fault characteristic component in the stator current at a frequency of $f_1 + mf_r$;
I_{ecnm}	maximum value of the fault characteristic component in the stator current at a frequency of $f_1 - mf_r$;
φ_{ecpm}	initial value of the phase angle for fault characteristic component at a frequency of $f_1 + mf_r$;
φ_{ecnm}	initial value of the phase angle for fault characteristic component at a frequency of $f_1 - mf_r$;
$\omega_1 = 2\pi f_1$	stator supply angular frequency;
$\omega_r = 2\pi f_r$	rotor angular velocity;
φ	initial phase angle of the fundamental supply current.

This gives rise to a number of components in the instantaneous power, namely a dc component, a component at a frequency of $2f_1$, components at frequencies of $2f_1 \mp mf_r$, and additional components at frequencies of mf_r . In [13], it was

also shown that for a similar analysis where broken rotor bars were present, additional components at $2ksf_1$ should be seen in the instantaneous power, where s is the slip defined as

$$s = \frac{f_1 - pf_r}{f_1} \quad (2)$$

where p is the number of pole pairs. It is easy to show that in the case of eccentricity, when $m = 2p$, then a characteristic component at a frequency of $2sf_1$ in the instantaneous power should be seen. Indeed, the experimental results in [13] confirm this, where the Fourier transform of the instantaneous power from a three-phase squirrel-cage induction motor was analyzed. The $2sf_1$ component appears in the case where the machine had an induced eccentricity, and this component increased in magnitude when the motor had increasing numbers of broken rotor bars.

These “additional components” (mf_r and $2ksf_1$) may not be the only frequency components characteristic of eccentricity and broken rotor bars. Indeed, Tavner [9] reports that frequency components of $2ksf_1/p$ and $2k(1-s)f_1/p$ will be observed when a broken rotor bar occurs. These components arise from the interaction of the electromagnetic air gap torque and the mechanical torque reaction, dependent upon the drive inertia. They are seen in the power signal as there is coupling between the shear stress field supporting the torque reaction and the air gap magnetic field.

There are similarities between the effects of rotor electrical imbalance and an eccentric rotor which mean that a rotor imbalance, whether due to electrical effects or an eccentric air gap, is likely to give rise to additional components which are indicative of both these faults, albeit their magnitudes may differ. This means that the $2ksf_1/p$ and $2k(1-s)f_1/p$ components may also appear in the case of an eccentric rotor. To date, the authors are not aware of a full mathematical analysis of these current and power frequency components and further work will be required to establish this for both rotor winding asymmetry and eccentric rotors in induction machines.

Analysis of the $2ksf_1$ and $2ksf_1/p$ frequency components of the instantaneous power has the advantage that these are generally of low frequency. For a wind turbine, sampling of sensors that may be used for the detection of modes of oscillation of the turbine structure are required to be in this same low frequency range.

B. Analysis of the Power using Wavelets

MCSA and instantaneous power analysis of electrical machines has been done using Fourier transforms, e.g., [13], [15], [16]. This yields satisfactory results when the machine is running at fixed speed but is more problematic to apply in variable-speed situations. The majority of large modern wind turbines operate under variable-speed conditions.

Short-term Fourier transforms (STFTs) may be used, however, they have the drawback of giving a fixed time and frequency resolution at all frequencies and there will always be a tradeoff between frequency and time resolution. Wavelet transforms have the feature that they give better frequency resolution

(but worse time resolution) at low frequencies and better time resolution (but worse frequency resolution) at high frequencies. This is in general desirable for most practical signals where higher frequency components tend to be short-lived whereas lower frequency components tend to be longer in duration. As described earlier, the use of wavelets has been investigated for the detection of eccentricity and broken rotor bars in dc and induction machines by the analysis of machine currents. In this paper, we adopt the use of wavelets for the analysis of the machine instantaneous three-phase power to deal with these issues of variable speed. There are other potential tools for time- and frequency-domain analysis of the power signal, however, the purpose of this paper is not to provide an in depth analysis of these techniques, rather to illustrate the practical application of a signal-processing technique that is able to cope with a non-stationary signal for the purposes of detecting a fault on a wind turbine generator shaft.

The continuous wavelet transform (CWT) of a time series $x(t)$, in this paper, and the instantaneous three-phase power $p(t)$, is given by

$$W_{a,b}(t) = \int_{-\infty}^{\infty} x(t)\psi_{a,b}^*(t)dt. \quad (3)$$

This is a function of the so-called daughter wavelets defined as transformations of the mother wavelet

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \quad (4)$$

where t is time, a is the scale applied to the mother wavelet, and b is the translation applied to the mother wavelet.

The CWT, thus, gives information with regard to the correlation between the mother wavelet and the signal, which is being analyzed in both time domain (related to b) and frequency domain (related to a), respectively. The mother wavelet used, in this paper, is based on the Morlet wavelet as defined in the MathWorks MATLAB software Wavelet Toolbox, namely

$$\psi(t) = e^{-\frac{t^2}{2}} \sin(\sigma t) \quad (5)$$

where the default value of $\sigma = 5$ was used that represents a reasonable balance between frequency and temporal resolution.

The Morlet wavelet is essentially a sinusoidal oscillation, which is localized using a Gaussian function. It is, therefore, well suited to the analysis of a signal where a periodic shock event is to be detected, such as is the case with a shaft misalignment and a worn bearing. The discussion described in Section II has indicated that perturbations such as rotor eccentricity resulting from shaft misalignment will modulate the power signal and the frequency of this modulation will vary in the case of a variable-speed wind turbine. The objective of using the Morlet wavelet transform was to localize a given variable frequency component ($2ksf_1$ and $2ksf_1/p$) in time and determine its magnitude. This was then used as an indicator of the severity of shaft misalignment, which could be the precursor to eventual bearing failure.

The aforementioned CWT was applied to the power output from generators in both a test rig and a variable-speed wind turbine, sampled at 3 kHz and 32 Hz, respectively. The test

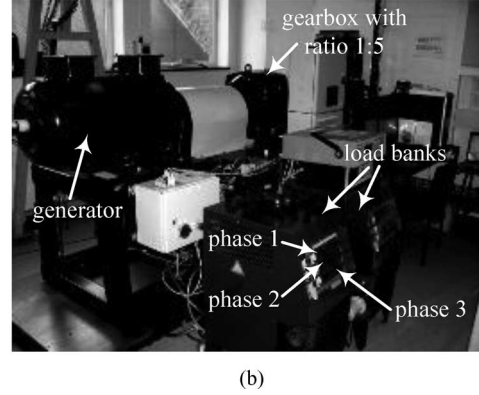
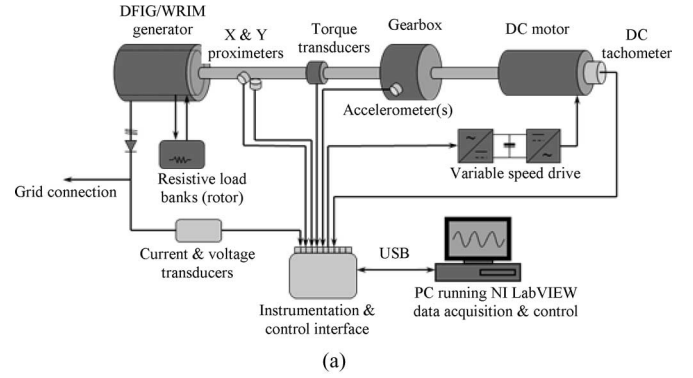


Fig. 1. Wind turbine condition monitoring test rig. (a) Schematic presentation of the test rig. (b) Photograph of the test rig.

rig was sampled at a higher frequency simply to capture higher frequency components in other signals not considered in this paper. The results of these analyses are described in the following section.

III. RESULTS OF GENERATOR POWER ANALYSIS

A. Test Rig

A test rig was used to simulate a fault as might be seen in a variable-speed wind turbine with a DFIG. The test rig consisted of a 50-kW dc variable-speed drive connected via a 5:1 gearbox to a four-pole DFIG connected as a wound rotor induction generator as shown in Fig. 1.

The test rig was controlled using LabVIEW software to drive the dc motor and collect data from the drive train, including generator torque, rotor speed, current, and voltage. The motor could be driven at a variable speed to realistically simulate the changing aerodynamic torque on a wind turbine rotor. A number of faults could be applied to the wound rotor induction generator, including circuit imbalance by adjusting the balance of the rotor resistors in the resistance bank, to emulate the effect of a faulty or eccentric rotor. The test rig is described in more detail in [13].

The rotor circuit imbalance was applied under both fixed and variable-speed operating conditions. The test rig was run for a period of 100 s and the rotor circuit imbalance applied and removed alternately in 20 s bursts. In this way, the rig was made to operate during the experiments under alternately “healthy” and “faulty” conditions. Data were sampled at 3 kHz. A CWT, as described above, was applied to the time series of the

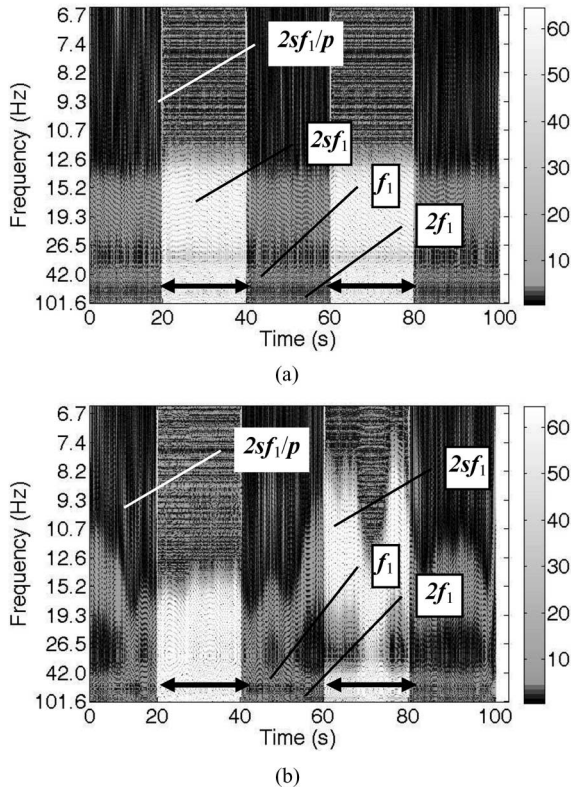


Fig. 2. CWT of test rig power signal for circuit imbalance during (a) fixed speed and (b) variable-speed conditions. The double-headed arrows show the condition when the circuit imbalance was applied ("faulty" state) otherwise the machine was in the healthy state.

three-phase power output, calculated from the three-phase current and voltage measurements.

The test rig experiments were performed with alternating periods of "healthy" and "faulty" conditions, to allow a relative comparison between frequency components in the power signal under these two operating conditions. Fig. 2(a) shows the result of this CWT for the test rig run at a fixed speed with the circuit imbalance applied periodically. The scale parameter a has been converted to a frequency in Hertz on the vertical axis and the time in seconds is shown on the horizontal axis. Because of the characteristics of the wavelet transform, the bandwidth increases with increasing frequency (decreasing a). There are three relatively prominent bands that can be seen: the most prominent corresponding to $2sf_1$, and two further bands at f_1 and $2f_1$. The magnitude of these three bands clearly shows an abrupt increase when the circuit imbalance was applied (faulty condition). There is some evidence of a band at $2sf_1/p$ though its magnitude is significantly less than the other three bands.

Fig. 2(b) shows a similar CWT for the case where the test rig was run at a variable speed to simulate the case of a variable-speed wind turbine under changing wind speed conditions when operating between cut-in and rated wind speed. Once again, the three frequency bands corresponding to $2sf_1$, f_1 and $2f_1$ can be seen. The band at $2sf_1/p$ is more visible than for the fixed speed case. As expected the f_1 and $2f_1$ bands are horizontal lines, whereas the $2sf_1$ band varies in frequency as the slip of the generator varies in response to changes in rotor speed.

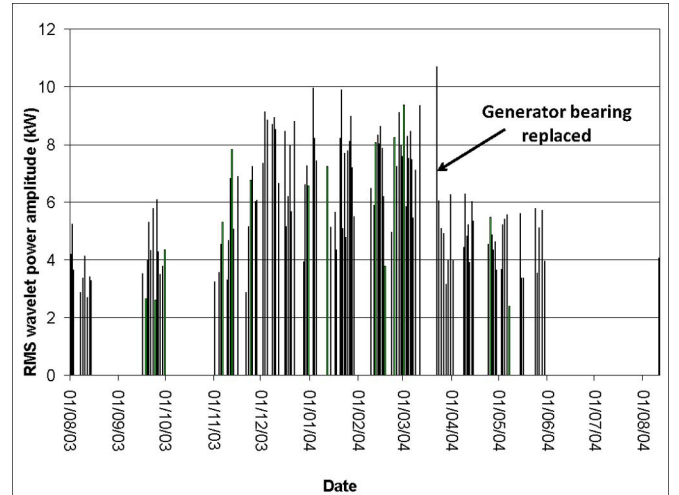


Fig. 3. Daily root mean squared value of the CWT of the 1.5-MW wind turbine power corresponding to a frequency of $2sf_1/p$.

Also, the magnitudes of all three bands show an abrupt increase in the faulty condition when the circuit imbalance is applied. The increase in magnitude of the $2sf_1/p$ band is less obvious. These frequencies were all much less than the 3 kHz collection frequency of the test rig.

It should be noted here that the magnitude of the faults applied represent extreme conditions. In reality, the level of fault seen in an operational wind turbine will be lower. The point of monitoring such as the $2sf_1$ component using a wavelet is that its magnitude shows an increase under fault conditions and that it can be tracked easily in time even though its frequency may be constantly changing.

B. Operational Wind Turbines

A 1.5-MW variable-speed pitch-regulated wind turbine with a DFIG was instrumented to provide moderate frequency (32 Hz) data for a number of operational parameters including rotational speed and three-phase power output. Additional sensors were installed on the turbine to provide high-frequency vibration data on the gearbox and generator. Ten-minute data from the standard supervisory control and data acquisition (SCADA) system were also collected. Data were recorded over a period of two years and a CWT applied to the three phase power data. In order to reduce power signal noise, the power data were filtered so that only values less than 40 kW were used in the CWT transform. This meant that this was applied only when the turbine was operating just above its cut-in wind speed. From the CWT transformed values, the rms values of the power data corresponding to frequencies of $2sf_1$ and $2sf_1/p$ were calculated for each day, where available. Clearly, the turbine may not necessarily have been operating in the low power range above cut-in on every day. The $2sf_1$ component was quite small in magnitude and showed little change in magnitude throughout the 2-year period, however, the $2sf_1/p$ component was clearly visible and did show changes in magnitude during the period. The results of this analysis for the $2sf_1/p$ frequency component are shown in Fig. 3. It can be seen from this figure that the daily rms

value showed an increase in November 2003. In January 2004, a generator misalignment was noted by the operator and an attempt was made to correct this by other means. This attempt was not successful and in March 2004, the generator bearing failed. When the bearing was replaced, the wavelet rms values of the $2sf_1/p$ frequency component from the three phase power output were reduced in magnitude, as shown in Fig. 3.

Monitoring of the $2sf_1/p$ frequency by use of a CWT, therefore, detected the generator shaft misalignment at least 3 months before the bearing failure occurred.

A similar analysis was undertaken for a 2.5-MW-variable-speed pitch-regulated wind turbine with a DFIG. In this case, 30-Hz data were collected over the period of 1 year. In addition, vibration data from the gearbox and generator were collected. Fig. 4(a) shows the daily rms CWT power amplitude corresponding to $2sf_1/p$. In this case, the $2sf_1$ component could not be monitored as it was outside the sampling frequency. For comparison, Fig. 4(b) shows the band-filtered radial vibration velocity values over the same period in the frequency range 10–30 Hz from a vibration sensor placed on the generator casing near the drive-end bearing. This turbine was one of a group of five and increased generator drive-end bearing vibration had been reported on this turbine as compared with the other turbines. This was first picked up in December 2005. Around this time, the CWT power amplitude shows an increase. During the period from 20th March to 24th April 2006, this vibration level increased still further, as seen in Fig. 4(b). The CWT power amplitude values also increased during this period, as seen in Fig. 4(a). The increased vibration was found from inspection to be due to shaft misalignment. Corrective maintenance was undertaken at the beginning of May 2006, and initially some small reduction in the vibration level and CWT power amplitude was noted, but these levels started to increase again. At the beginning of July 2006, an attempt was made to realign the generator shaft once again. However, high vibration levels were still present. It was not until around September 2006 that the levels started to decrease slightly due either to the settling of the generator or to wear of the bearing. The CWT power amplitude values also decreased slightly over this period. It should be noted that bearing failure had not occurred over this period, so it is unlikely that such large increases in the CWT power amplitude would be seen, compared with the 1.5-MW wind turbine. Although, the *reduction* in the CWT and vibration signal levels would not in themselves indicate possibly bearing problems, the time history of the levels in conjunction with the maintenance log would give the necessary information assuming a complete failure modes and effects analysis (FMEA) had been carried out.

Although the result of analyzing the power signal using the CWT is not as clear cut in the case of the 2.5 MW wind turbine, in terms of detecting shaft misalignment, there is nonetheless sufficient change in the CWT power amplitude over the monitoring period, consistent with independent vibration monitoring, to conclude that DFIG rotor eccentricity due to misalignment has been detected by analysis of the $2sf_1/p$ frequency component. The technique is certainly worthy of further investigation on a larger number of similar wind turbines incorporating DFIG machines. The technique could also be applied to fixed-speed wind

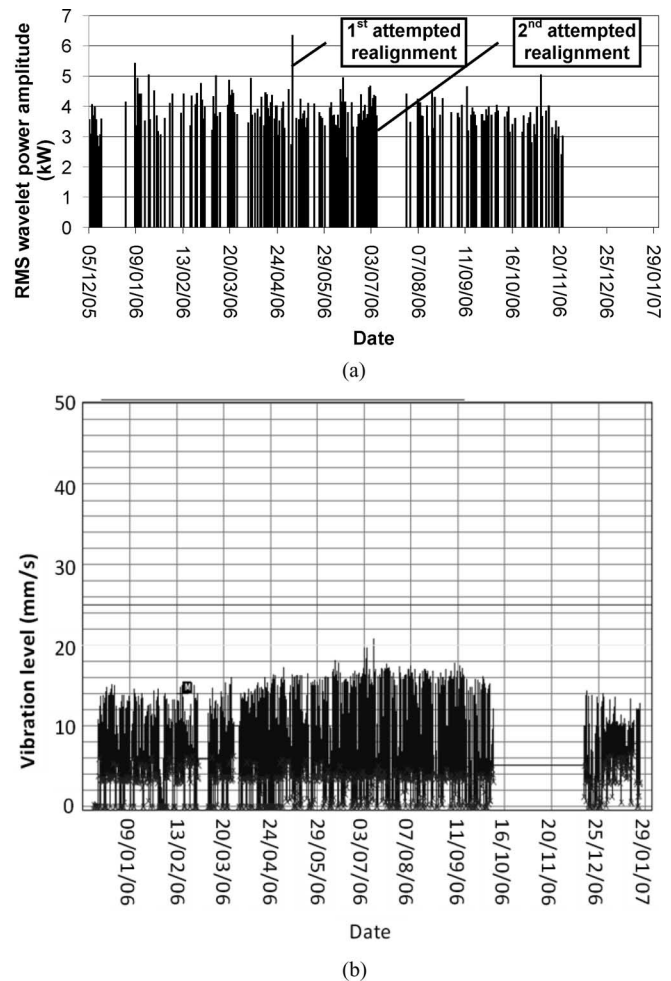


Fig. 4. (a) Daily root mean squared value of the CWT of the 2.5-MW wind turbine power output corresponding to a frequency of $2sf_1/p$. (b) Vibration level in the frequency range 10–30 Hz measured on the casing close to the generator drive-end bearing of the wind turbine over the same period.

turbine with induction generators but CWT would then not be essential.

IV. CONCLUSION

The move to offshore wind farms has highlighted the requirement for predictive and pro-active maintenance. One way to do this is through intelligent condition monitoring. Bearing failures in gearboxes and generators can result in lengthy and costly downtime. One way to monitor the health of such subassemblies is through relatively costly vibration monitoring. A lower cost approach, which may yield sufficient information for bearing health, is to monitor the wind turbine power output, already available from the turbine control system.

Traditional SCADA systems record data at 10-min intervals. Additional logging at a modest frequency of ~ 30 Hz could be used in the future to measure mechanical modes of vibration in a turbine using accelerometers and strain gauges to allow advanced control in order to reduce fatigue loads.

It has been shown, in this paper, that by monitoring the power at these modest frequencies and by applying a CWT to the

resulting data, the magnitude of the component at twice slip frequency divided by pole pairs ($2sf_1/p$) may be tracked as an indicator of rotor eccentricity in a DFIG. Rotor eccentricity is often the result of increased bearing wear and an indication of potential failure. It is possible that other potential faults may give rise to an increase in the $2sf_1/p$ component and this warrants further mathematical and experimental investigation. Nevertheless, it has been shown that rotor eccentricity may be detected using this component.

The advantage of using a wavelet is that it can be used to track the $2sf_1/p$ frequency component under varying rotor frequency (slip), which is more problematic when using the more traditional frequency Fourier transform. Another advantage of monitoring the $2sf_1/p$ component is that it is generally at a low frequency.

Although the application of the CWT can be computationally expensive, it is only the $2sf_1/p$ component that needs to be tracked in time and if this were done this would substantially reduce the required computational resources.

This technique described in this paper could be applied to any variable-speed wind turbine using an induction generator and would require only modest additional instrumentation over and above the standard SCADA system.

Further work will be required to establish a full mathematical analysis of the relationship between frequency components in the current and power signal for both rotor winding asymmetry and eccentric rotors in induction machines. Future work is also required to apply this method to other operational wind turbines, which may be suffering from incipient generator bearing faults, and to use the detection of a faulty condition to potentially predict failure some time in advance. The analysis presented in this paper has shown in a subjective way that shaft misalignment has been detected, but further work is required to turn this technique into a predictive tool where detection of potential bearing failure is automated. This will require the analysis of a number of machines to establish thresholds for healthy and faulty machines. Once sufficient data have been collected for a particular type of machine, it would be possible to set appropriate alarm levels, which would be automatically triggered. These levels would alert operators to the possibility of bearing failure and the requirement for proactive maintenance. Work is also necessary to assess whether this technique could be used to detect gearbox-bearing problems.

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